Wide-Bandgap Semiconductor Devices for Automobile Applications

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Abstract

In this paper, we discuss requirements of power devices for automobile applications, especially hybrid vehicles, and the development of GaN power devices at Toyota. We fabricated AlGaN/GaN HEMTs and measured their characteristics. The breakdown voltage was over 600V. The drain current with a gate width of 31mm was over 8A. Observation by a thermograph image of the device under high current operation showed the AlGaN/GaN HEMT operated at more than 300ºC. All the results of our GaN are really promising to realize high performance and small size inverters for future automobiles.

INTRODUCTION

Development and improvement of hybrid vehicles (HVs), electric vehicles (EVs) and fuel cell hybrid vehicles (FCHVs) are now widely recognized as one of solutions of the CO_2 problem of the earth scale and the exhaust gas problem of urban areas. These vehicles need high electric power inverters with high energy efficiency. Si Insulated Gate Bipolar Transistors (Si IGBTs) are wildly used in the inverters, but these devices have limitation of performances due to their material property. Devices with higher performances have been strongly required for future vehicles. In this paper, we discuss requirements of wide-bandgap semiconductor devices for automobile applications, especially hybrid vehicles, and the development of GaN power devices.

Figure 1 shows the road map of the power electronics [1]. Their power densities have been increasing year after year. The inverters installed in Toyota's hybrid vehicles, such as Prius and RX400h have very high power densities as shown in the figure. However, HV and FCHV systems of the next generation will require much higher power densities with lower energy loss, smaller size and lower cost. It is difficult to realize such higher power density systems with Si-IGBTs, because of their material limits. Therefore, we should develop new power devices made of new materials for these systems. Theoretical performances of several semiconductor materials are shown in Table 1, where wide-bandgap semiconductors clearly have advantages compared with Si. This is the big motivation for us to develop novel switching devices made of wide-bandgap semiconductors such as SiC and GaN.

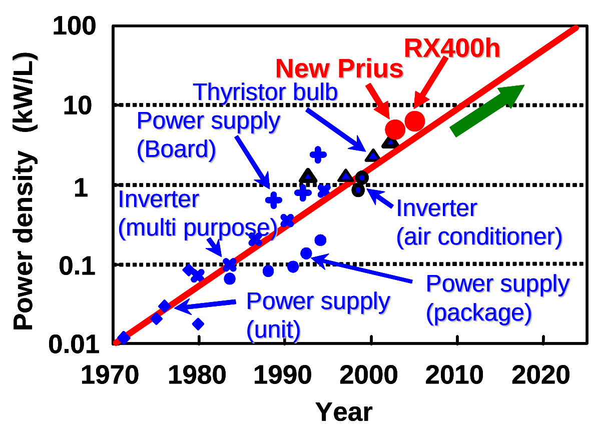

Fig.1 Road map of power electronics

Table.1 Normalized figures of merit of various semiconductors

	Si	GaAs	4H-SiC	GaN
JFM	1	11	410	790
KFM	1	0.45	5.1	1.8
BFM	1	28	290	910
BHFM	1	16	34	100

JFM:Johnson's figure of merit for high frequncy devices=$(EbVs/2\pi)^2$

KFM:Keyes's figure of merit considering thermal limitation=$\kappa(EbVs/4\pi\varepsilon)^{1/2}$

BFM:Baliga's figure of merit for power switching=$\varepsilon\mu Eg^3$

BHFM:Baliga's figure of merit for high frequency power switching=μEb^2

REQUIREMENTS OF POWER DEVICE FORS AUTOMOBILE APPLICATIONS

To realize the next generation hybrid systems, the following performances will be required for the devices.

1) Normally-off Operation

Most of the efforts on GaN base devices have been mainly directed towards the normally-on one, and there are a few reports for the normally-off one. The normally-off device is one which the drain current does not flow at gate voltage of 0V. Si-IGBTs used in the present inverters are normally-off operation devices. Likewise, the normally-off operation device is required to simplify the inverter circuit for future automobiles.

2) High Breakdown Voltage

Figure 2 shows the relationship between the motor power of Toyota's HVs and power source voltage of these systems. The first generation Prius had been on market at 1997, and the inverter in this hybrid system was connected to directly to a battery of 277V. The new Prius has been on the market since 2003, and the raised voltage can take values from 202V of the battery up to a maximum of 500V using DC/DC converter [2]. The new Toyota's HVs need high motor power with high power source voltage as shown in Fig. 2. The maximum breakdown voltage of devices used these inverters is about 1.1kV [3]. It will be highly probable that the breakdown voltage of devices increase in future due to protection against surge voltage and so on. On the other hand, it is likely that the upper breakdown voltage of devices in inverter system is about 2kV due to breakdown voltage of condensers and insulation films.

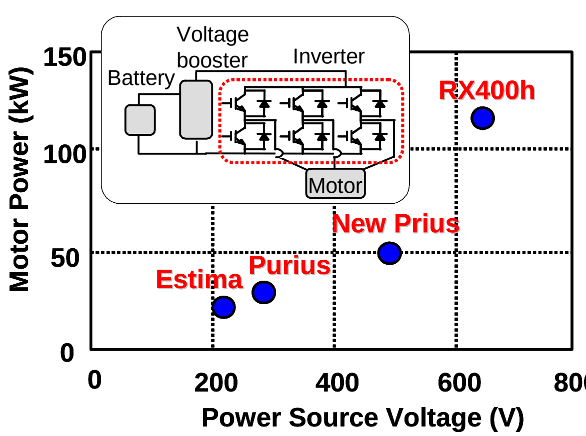

Fig.2 Power source voltage vs Moter power

3) Low On-resistance and High Current Operation

In order to decrease power loss in inverter systems, it is necessary to decrease on-resistance of the devices and to increase the current densities up to several hundreds A/cm^2.

4) High Temperature Operation

Si devices stop working at about 150°C, because the power loss increase owing to an increase of the leakage current at off state in high temperature circumstance. In contract, it is probable that GaN devices will operate over 200ºC, because the energy bandgap of GaN is wider than that of Si. In the present hybrid systems, there are two cooling systems, one is the cooling system for an engine and the other is that for the inverter, and the temperature of cooling water for the inverter is lower than that for an engine. If the GaN devices operate over 200ºC, the cooling system of hybrid vehicles will be simplified and its cost will become lower.

5) Vertical Operation

Up to date, most of the efforts on the GaN base devices have been mainly directed towards the lateral operation one. However, it is necessary to vertical operation devices for automobile applications. First, the vertical devices lead to smaller chip size. Secondly, it is possible to decrease the power loss and the dissipation of electrode at high current operation.

DEVELOPMENT OF GAN POWER DEVICES

1) Normally-off Operation

The study of GaN based device has been mainly focused on the normally-on operation device for microwave power applications, for example, the base station. Recently, there have been a few reports on the normally-off operation GaN devices for power electronics applications, and the threshold voltages (Vth) of these devices are about +0.3V [4] [5]. However, the devices with high drain current and very low on-resistance are not still realized. Because, most of these devices are Schottky gate type, and the maximum voltage applied to the gate electrode is about +2V due to gate forward current. Therefore, it is difficult to control high current by a Schottky gate electrode. On the other hand, the insulated gate can be applied higher than about +2V. In order to realize the normally-off devices with high current operation and low on-resistance, the key issue is the formation of gate insulated films with good quality. We investigated SiO_2 film formed by Low Pressure Chemical Vapor Deposition (LP-CVD) at high temperature [6]. Results of the interface-state density calculated with Terman method are shown in Fig. 3. The curve of the interface state density had two peaks at about -0.4eV and -0.7eV from the conduction band, and both of the interface state densities were 2x10^{11}/cm^{2}eV. We are developing the normally-off device using SiO_2 film.

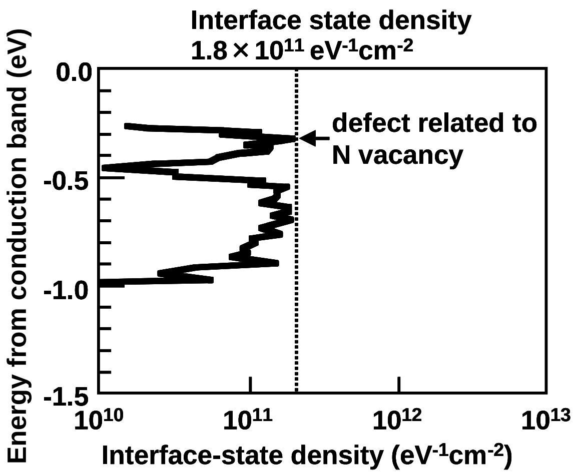

Fig. 3 SiO_2/GaN interface-sate density

2) High breakdown voltage

A GaN-HEMT was reported in recent years with a break down voltage of 1.3kV [7]. We have fabricated insulated gate HEMTs, and measured the breakdown characteristics. Figure 4 shows the result of breakdown characteristics at the gate bias of -30V. The gate-drain length and the gate width of this device are 20μm and 440μm, respectively. The breakdown voltage was over 600V. It is necessary to improve the breakdown voltage (up to 1.2kV). We would now like to go on to develop these devices by examining the termination structure, for example, the field plate structure.

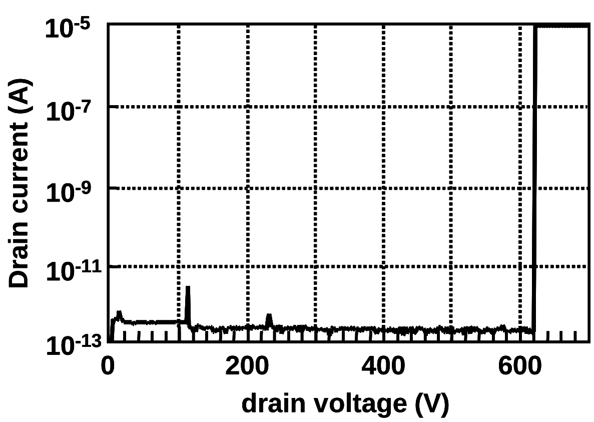

Fig. 4 Breakdown characteristic

3) Low On-resistance and High Current Operation

To examine the possibility of GaN, we fabricated a large size GaN power HEMT with a gate width of 31 mm (Fig. 5), and verified a high current operation [6]. The drain current obtained 8A under pulse measurement (Fig.6) showed enough high current can be obtained. The specific on-resistance was about 5mΩ-cm^2. The specific on-resistance is needed to decrease further.

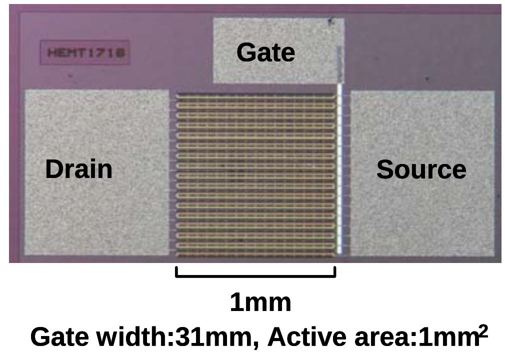

Fig. 5 Photograph of fabricated GaN-HEMT

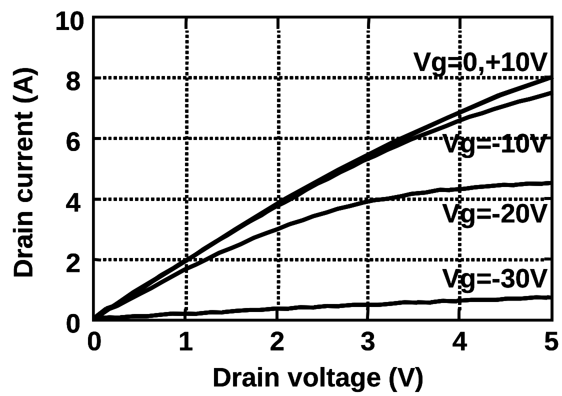

Fig. 6 I_D-V_D characteristic under pulse condition

4) High Temperature Operation

Observation by a thermograph image of the device under high current operation (Fig.7) showed the GaN HEMT operated at more than 300ºC [8]. The gate width and the chip size of this device were 31mm and 2x4mm^2, respectively. The Active area was about 1x1mm^2. The bias condition was V_D=2.6V and I_D=1.3A under DC condition. These results indicate that GaN power devices are promising for future automotive systems operated in high temperature circumstance.

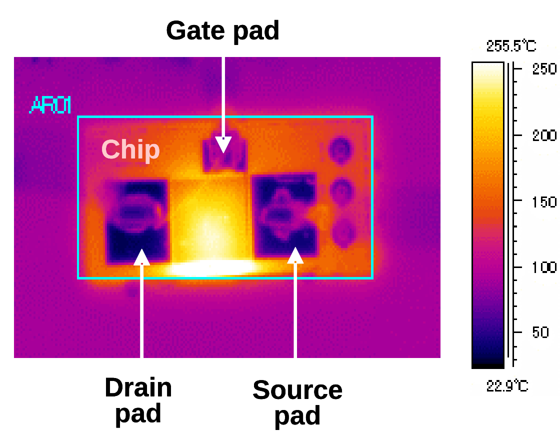

Fig. 7 Thermograph image under high current operation

5) Vertical Operation

We have also developed a vertical operation device [9] in order to decrease the on resistance. We fabricated the vertical operation device on a freestanding n-type GaN substrate. Figure 8 shows the current-voltage characteristics. It was found that by using a free standing GaN substrate, vertical current between source and drain was really well controlled by the gate bias. The leakage current at pinch-off state was less than 10^{-9}A with the gate length of 4μm and the gate width of 300μm.

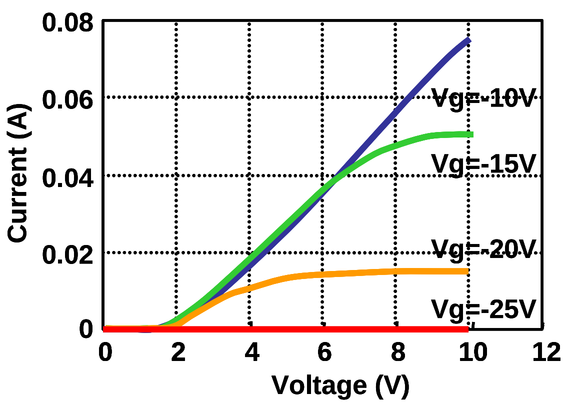

Fig. 8 I-V characteristic of vertical operation device

CONCLUSIONS

GaN power devices are excellent candidates for automobile applications. We fabricated AlGaN/GaN HEMTs and measured their characteristics. The breakdown voltage was over 600V. The drain current obtained 8A at device with a gate width of 31mm. All the results of our GaN are really promising to realize high performance and small size inverters for the future automobiles.

On the other hand, many problems of GaN power devices are remained unsolved, for example, the characterization of reliability, a decrease of defects in freestanding GaN substrate. Furthermore, normally-off devices with low on-resistance and high breakdown voltage are required for future automotive systems.

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ACRONYMS

HEMT: high electron mobility transistor
HV: hybrid vehicle
EV: electric vehicle
FCHV: fuel cell hybrid vehicle
IGBT: insulated gate bipolar transistor